

University of Pécs  
Doctoral School of Chemistry

**The impact of mass transfer on efficiency in reversed  
phase liquid chromatography**

**PhD thesis**

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# 1 Introduction

During the recent years, a number of chromatographic columns with various types of packing materials – such as traditional fully porous and core-shell particles in a wide range of diameters, and monolithic packings – have been introduced. The most frequently used columns dedicated to the recent ultra-high performance liquid chromatography (UHPLC) instrumentation are narrow and short (2.1 mm ID and 50 mm length), and are packed with sub-3- $\mu\text{m}$  or sub-2- $\mu\text{m}$  particles [1–4]. The use of core-shell particles is also wide spread to gain higher efficiency with traditional liquid chromatography systems, or reach the peak performance in fast liquid chromatography. The performance of the superficially porous particles is typically higher than that of the conventional packings. The efficiency of the columns packed with 2.6  $\mu\text{m}$  core-shell particles is nearly the same as that of columns packed with sub-2- $\mu\text{m}$  fully porous particles, but they can be operated at lower pressures, consequently lesser efficiency loss due to thermal effects is observed [5, 6].

Besides the unusually low value of eddy dispersion and thus the reduced longitudinal diffusion caused by the presence of the solid core, the decrease of the intraparticle diffusion is particularly important in core-shell packed columns. The mass-transfer of the solute through the internal network of the mesopores inside the particles is derived from two parallel diffusion mechanisms. One through the mobile phase that fills the pores, and the other along the stationary phase surface. The advantages of the faster mass-transfer to the adsorption sites of the stationary phase surface, i.e. the higher intraparticle diffusion are more expressive during the analysis of macromolecules, such as proteins and other biomolecules, due their smaller diffusion coefficients [7]. Besides the use of the well-known and widely used fully-porous or core-shell packing materials, another potential is in the development of monolithic silica columns, where improved efficiency can be achieved and moderate column pressures are sufficient to maintain high mobile phase flow owing to the small skeleton size and large (through-pore size)/(skeleton size) ratios [8–12].

The efficiency of a liquid chromatography measurement is determined by a number of additive contributions to the sample band spreading in the chromatographic column such as mobile phase dispersion, the external mass-transfer resistance at the particle boundary, the intraparticle-diffusion or the adsorption–desorption process on the surface of the stationary phase [13]. The fluctuation of local packing density provides the crucial part of the sample band dispersion in the mobile phase. In the packed bed, one can identify tightly and loosely packed regions; the velocity fluctuation that arises from that heterogeneity is the interchannel (short or long range) or transcolumn velocity bias [14]. Recent studies show that in case of the packed columns another band spreading contribution comes from the presence of the frits at the column ends and from the axial heterogeneity of the column originating from the column packing procedure. The above mentioned contributions have the most significant role in case of the separation of early eluting compounds ( $k < 2$ ), where mobile phase dispersion is the most dominant contribution to the band broadening [15].

Better efficiency can be achieved with given column geometry (i.e. with same column length and inner diameter) by decreasing the particle diameter of the column packing material [16, 17].

That leads to the simultaneous reduction of the analysis time too. However, the efficiency that can be reached in a column is inversely proportional to the particle size, the operating back pressure is inversely proportional to the square of the particle diameter too. The use of smaller particles leads to elevated operation pressure and optimum mobile phase velocity, which results in thermal dissimilarities in the column, through the generated frictional heat of the mobile phase [18].

When the column is thermostated, and the temperature of the column wall is kept constant, a radial temperature gradient can be observed in the mobile phase between the center and the wall of the column. That means that the velocity of the mobile phase will be higher at the middle of the column than near to the wall. Several studies prove that the efficiency loss caused by the thermal effects can be significant in case of very fine packing materials [19,20]. With the insulation of the column the radial temperature gradient can be eliminated. The efficiency loss due to the thermal dissimilarities in the mobile phase can be evaluated according to the general rate model of chromatography, using various methods for the characterisation of the different mass-transfer contributions to the observed peak variances in the examined columns.

The study covers the evaluation of the kinetic performance of several reversed phase (C<sub>18</sub>) columns packed with fully porous and core-shell particles with various particle diameters and the performance of a silica-based monolithic column, regarding the contributions of the intraparticle diffusion, the axial heterogeneity of the packed bed, the frictional heating or the mobile phase dispersion by using the general rate model of chromatography [13].

Due to technical improvement in instrumentation, supercritical fluid chromatography (SFC) has recently gained increased attention in the fields of applications and theoretical investigations too [21–27]. In case of SFC, the mobile phase is kept under supercritical state using pressure and temperature conditions above its supercritical point. Most frequently carbon-dioxide is used as mobile phase, since it is non corrosive, easy to access and it is easy to maintain the supercritical conditions caused by its low critical point. The biggest advantage of the SFC technique is coming from the low viscosity of the supercritical fluid, that allow to use high flow rate in columns packed with very fine particles at negligible pressure drop and intraparticle plate height contributions.

Since the density of the supercritical fluid is strongly affected by its composition and by the pressure and temperature conditions, the mobile phase dispersion highly varies during the SFC separations. A number of studies investigated the dependence of retention factors in SFC on temperature, pressure, or the density of the mobile phase [28–31].

The comparison of SFC and UHPLC techniques was done by using the stochastic model of chromatography introduced by Giddings [16] and refined by numerous authors [32–35]. The model describes the separation process as a random migration, and randomly occurring adsorption–desorption of the molecules in the chromatographic column. The advantage of the use of the stochastic model is that it simplifies the correction for the mobile phase band spreading. Since HPLC columns can be installed and used in SFC, a direct comparison of the two modes of operation can be obtained.

## 2 Research objectives

1. Analysis of frictional heat on column efficiency
  - (a) The measurement of efficiency with small molecules with the thermostating and the insulation of the examined columns.
  - (b) The determination of the geometrical parameters i.e. the porosity values of the chosen columns packed with sub- $2\mu\text{m}$  core-shell and fully porous particles with total pore blocking experiments.
  - (c) The determination of the external obstruction of the stationary phases with peak-parking experiments.
  - (d) The characterization and subtraction of the different contributions from the experimental plate height, for the determination of the effect of the thermal dissimilarities caused by the frictional heating of the mobile phase.
2. Comparison of the efficiency of vHPLC stationary phases
  - (a) The determination and comparison of the efficiency of different (monolithic and slurry packed) columns with a check-out sample containing the series alkylphenones under the same chromatographic conditions.
  - (b) The exploration of the efficiency differences between the examined columns.
  - (c) The analysis of the local efficiency at the vicinity of the column ends, by applying the column reversal method.
3. Analysis of the intraparticle diffusion of macromolecules
  - (a) The measurement of the efficiency of conventional and core-shell HPLC columns with insulin.
  - (b) The estimation and subtraction of the different mobile phase dispersion contributions from the observed sample band variance.
  - (c) The identification and examination of the band broadening caused by the intraparticle mass-transfer.
4. Comparison of the mass-transfer properties in SFC and UHPLC
  - (a) The measurement of the efficiency of the same reverse phased column in the two different chromatographic modes by injecting the series of alkylbenzenes.
  - (b) The calculation and the comparison of the mass-transfer coefficients provided by the stochastic model of chromatography applied on the experimentally recorded peaks.

## 3 Methods and Materials

### 3.1 Total pore blocking experiments

The TPB experiments covers the blocking of the stationary phases pores with hydrophobic solvent, and the measurement of the external voids with non mixable analytes for the exploration of the different porosity values in the examined columns. The used blocking agents was octane and dodecane for the fully porous and core-shell packed columns as blocking agent, respectively. The flush solvent was 10mM ammonium-formate. The column was washed at least 20 times of the column volume with isopropanol before the columns were filled with hydrophobic solvent. After that, the column was flushed with buffer until the baseline and the pressure stabilized. The column hold up volumes were measured using thiourea dissolved in buffer.

### 3.2 Peak parking experiments

The peak parking method is used to determine the effective diffusion coefficients of the analytes in the column. The PP measurements were performed using the corresponding mobile phase mixtures, - i.e the same mobile phase that was used during the measurements of the different analytes - and thiourea as sample, while the flow rate was set to 0.2 mL/min. The flow was stopped for  $t_p = 0, 30, 60, 300, 600, 1200, 2400, 3600$  seconds as the half of the void volume passes trough the column after injection. Each measurement was repeated three times.

### 3.3 Flow reversal method

The flow reversal method is capable for the analysis of the axial heterogeneity of the inner structure of the chromatographic columns, emphasizing the differences at the column ends. During the experiments, the columns were installed in the chosen flow direction, and an unrestrained marker (thiourea) was injected, while the flow rate was set to 0.2 mL/min. The flow was stopped when the sample band reached the selected region of the column (1, 2, 3 or 4 cm distance from the column inlet or outlet). After the pressure dropped to ambient, the column was disconnected and reinstalled in the opposite flow direction. Then the flow was restarted and the sample band was eluted from the column at the same end as it entered the column. In each case the flow was arrested for a total of 2 minutes, which was more than enough for the pressure relaxation and for the disconnection and reinstallation of the columns.

Since the flow is stopped and the sample band is let free to diffuse for a given time, an additional band variance is introduced, which can be easily subtracted by the determination of the axial dispersion coefficient with peak parking method [36,37].

### 3.4 Measurement of the effect of frictional heating on column efficiency

The homologous series of alkyl-benzenes, containing octyl-, decyl-, dodecyl-, tetradecyl- and octadecyl-benzene in 0.5 mg/mL concentration was injected at flow rates between 0.2 and 0.9 mL/min. Pure methanol was used as mobile phase. The standards were purchased from Sigma-Aldrich (Germany, Schnellendorf) and were dissolved in methanol as sample. Measurements were carried out on a Waters Acquity I-class UPLC instrument (Waters Corporation, Milford, MA, USA) equipped with diode-array detector. The examined chromatographic columns were a fully porous Waters BEH (1.7  $\mu\text{m}$ , 50  $\times$  2.1 mm) column, and a superficially porous Waters Cortecs (1.6  $\mu\text{m}$ , 50  $\times$  2.1 mm). The measurements next to adiabatic conditions were carried out by the insulation of the columns with polystyrene foam rubber, while the eluent was preheated to 25 °C. The thermostated measurements were carried out at 25 °C.

### 3.5 Comparison of the efficiency of novel vHPLC stationary phases

The experiments were carried out on a Waters Acquity I-Class UPLC instrument, the mobile phase was the premixed mixture of 65:35 v/v acetonitrile and water (Sigma-Aldrich, Germany, Schnellendorf) for each measurement. All measurements were carried out at constant 40 °C column temperature while the injection volume was 0.2  $\mu\text{L}$ . The system void volume was around 1  $\mu\text{L}$  with the optimization of the tubing. Five different reversed phase (C<sub>18</sub>) chromatographic columns designed for fast liquid chromatography with the same geometrical parameters (2.1  $\times$  50 mm) provided by GL Sciences and Phenomenex were tested during the experiments under the same experimental conditions.

Agilent check-out sample (Agilent Technologies, Palo Alto, CA, USA) containing acetanilide, acetophenone, propiophenone, butyrophenone, benzophenone, valerophenone, hexanophenone, heptanophenone and octanophenone in 100  $\mu\text{g}/\text{mL}$  concentration was injected to evaluate the kinetic performance, and thiourea was used to determine the void volumes of the columns. The flow rate was set over the range 0.05–1.0 mL/min.

### 3.6 Analysis of the intraparticle diffusion of macromolecules

For the analysis of the intraparticle diffusion, solution of human insulin (Sigma-Aldrich, Germany, Schnellendorf) in 1.0 mg/mL concentration dissolved in the eluent was injected as sample, while the column hold-up volumes were determined by the injection of thiourea standard. The injection volume was 1  $\mu\text{L}$  in each measurement. Chromatographic columns were an Agilent Zorbax (100  $\times$  4.6 mm, particle size 3.5  $\mu\text{m}$ ) purchased from Agilent, a Waters Xselection (100  $\times$  2.1 mm, particle size 2.5  $\mu\text{m}$ ) a Phenomenex Kinetex (100  $\times$  4.6 mm, particle size 2.6  $\mu\text{m}$ ) a Phenomenex Aeris Peptide (100  $\times$  4.6 mm, particle size 3.6  $\mu\text{m}$ ) and a Phenomenex Aeris Widepore (100  $\times$  4.6 mm, particle size 3.5  $\mu\text{m}$ ).

The experiments were carried out on an Agilent 1290 Infinity UHPLC instrument (Agilent Technologies, Palo Alto, CA, USA) equipped with diode-array detector. Agilent Chemstation software was applied on the UHPLC system and used for the determination of the first and second central moments of the samples peak.

The eluent was a mixture of acetonitrile and water, with 0.1% trifluoroacetic acid (Sigma-Aldrich, Germany, Schnellendorf). The mobile phase flow-rate was set over the range 0.05–1.6 mL/min in case of the 4.6-mm ID columns, and 0.02–0.33 mL/min in case of the Waters Xselection column, to obtain the same linear velocities. The acetonitrile content of the eluent was changed between 28 and 29.5% v/v to maintain the same values of the retention factor on each column. The column thermostat was set to 25°C.

The internal and external porosity values determined by BacsKay et al. with a series of ISEC measurements [38] were used for the calculations of the mass-transfer properties of the columns.

### 3.7 Comparison in the efficiency between SFC and UHPLC techniques

The experiments were carried out on an Agilent 1290 Infinity ultra high pressure liquid chromatograph (UHPLC) (Agilent Technologies, Palo Alto, CA, USA) and on a Waters Acquity UPC<sup>2</sup> (Waters Corporation, Milford, MA, USA) supercritical fluid chromatograph (SFC). The instruments were equipped with diode-array detector. The same chromatographic column was installed in the two instruments, an Agilent Zorbax (100  $\times$  4.6 mm with the particle size of 3.5  $\mu\text{m}$ ) purchased from Agilent. Agilent Chemstation software was applied on the UHPLC system while the SFC instrument was controlled by the Empower 3 software. The injection volume was 2  $\mu\text{L}$ , and the flow-rate was set over the range 0.2–2.5 mL/min in each experiment. All measurements were carried out at constant 35°C column temperature. The injected sample was a mixture of the homologous series of alkylbenzenes: octylbenzene, decylbenzene, dodecylbenzene, tetradecylbenzene, octadecylbenzene and thiourea. The sample was prepared in 0.2 mg/mL concentration dissolved in methanol or heptane for the UHPLC and SFC measurements, respectively.

Two mobile phase compositions were used during the UHPLC experiments: one was a mixture of methanol and water 97.5:2.5% v/v and the other was pure methanol. The retention factor



(*k*) of the most retained compound (octadecylbenzene) was found around 14 and 7.2 at the different mobile phase compositions, respectively.

The SFC measurements were carried out under three different conditions. In the first two cases the eluent was pure CO<sub>2</sub>, while the ambient back pressure regulator (ABPR) was set to 105 and 150 bar (hereinafter low- and high pressure conditions), respectively. In the third case 9% of methanol was added to the mobile phase, and the ABPR was set to 105 bar, to obtain subcritical conditions.

## 4 Results

### 4.1 Effect of the frictional heat on efficiency in columns packed with sub-2 $\mu\text{m}$ particles

This work has demonstrated from experimental viewpoint that the mobile phase dispersion in columns packed with sub-2 $\mu\text{m}$  packings are significantly affected by the heat loss through their walls. This heat flux originates from frictional heating of the mobile phase against the stationary packed bed and a cause crucial efficiency loss,  $-h$  decrease with value between 0.4 and 1.2 – at elevated flow rates.

The efficiency loss do to the temperature heterogeneities in the column is in the same range as the loss that originates from the external mass-transfer resistance and axial dispersion contributions altogether.

Thermal heterogeneities are present in the same extent in the core-shell type and in the fully porous packing materials. There was no significant difference observed in the behaviour of the core-shell like or fully porous packings regarding to the frictional heating effects.

### 4.2 Comparison of the efficiency of novel vHPLC stationary phases

The kinetic performance of a series of 2.1  $\times$  50 mm packed and monolithic columns was tested and compared. The observed columns show rather similar plate height values close to  $H = 5 \mu\text{m}$  at the optimal mobile phase velocities.

Outstanding performance was ascertained for the monolithic MonoTower column, that provides sufficient efficiency next to significantly less pressure drop. Striking performance was found for early eluting compounds, what can be attributed to the moderate mobile phase dispersion caused by the simple column hardware by the absence of frits. The attachment of commercial frits to the ends of the monolithic column cause similar measurable properties to the packed columns for the entire range of retention factor, what proves the above mentioned phenomenon.

The Kinetex and Kinetex EVO columns packed with 2.6- $\mu\text{m}$  core-shell particles show similar efficiency as the columns packed with smaller particles. The Kinetex EVO column perform slightly better than its predecessor.

The sample band broadening in the immediate vicinity of the column ends was characterized by the column reversal method. It was demonstrated that the local efficiency at the two respective column ends differ from each other in every case, however the difference is negligible for the monolithic column. It seem to be the dependent of the manufacturer, whether the inlet or the outlet of the columns perform better, no clear statement can be given. The contribution of the column ends to the overall band variance was found between 0.78  $\mu\text{L}$  and 1.65  $\mu\text{L}$  for the different packed columns, and around 0.6  $\mu\text{L}^2$  in average on the monolith column.

Unique peak compression effect of the flow reversal was found, - i.e the peaks observed with reversed flow are always narrower and more symmetrical than the peaks obtained without reversing the flow, that can be attributed to the self compensation effect of the interchannel multipath dispersion. Accordingly, the local plate height was found smaller in every case than the one we get for the unretained thiourea after a simple injection without arrested and reversed flow.

### 4.3 Analysis of the intraparticle diffusion of macromolecules in different stationary phases

According to the results of the experiments made with insulin on different HPLC columns, there is no significant difference in respect of the intraparticle diffusion coefficients, although the fully porous particles shows slightly slower intraparticle mass-transfer.

Mobile phase velocity dependent intraparticle diffusion coefficients, and so, surface diffusion coefficients were found, due to the pressure dependent retention of the insulin sample. As an example, the intraparticle diffusion coefficients observed in case of the Xselection fully porous column increase from  $1.66 \times 10^{-8}$  cm<sup>2</sup>/s to  $1.88 \times 10^{-7}$  cm<sup>2</sup>/s, as the linear mobile phase changes from 0.012 (cm/s) to 0.38 (cm/s).

The analysis of the intraparticle mass-transfer highlight that the surface diffusion has a crucial role in the intraparticle movement of the macromolecules. The values of the pore diffusion coefficients are at least one order of magnitude lower than the values of the surface diffusion coefficients that are between  $1.59 - 3.98 \times 10^{-8}$  cm<sup>2</sup>/s at the highest flow rate used for the examined columns.

Significant differences were obtained in the pore diffusion between the fully porous columns and the core-shell packed columns caused by the dissimilarities of the intraparticle obstruction and of the hindrance factors. The value of  $D_p=4.72 \times 10^{-12}$  cm<sup>2</sup>/s was found for the fully porous Zorbax column, while the coreshell packed Kinetex Aeris Peptide column with corresponding particle and pore diameters provided  $D_p=4.48 \times 10^{-11}$  cm<sup>2</sup>/s.

### 4.4 Comparison of the efficiency of SFC and UHPLC techniques

The study of the chromatographic behaviour of small molecules in supercritical fluid chromatography and in reversed phase liquid chromatography with the stochastic model of chromatography shows the broader variation of the mass-transfer properties in SFC than in liquid chromatography. This is mostly due to the varying of the mobile phase density with the flow-rate in SFC mode.

The residence times in the stationary and in the mobile phases depend on the flow-rate in both chromatographic method, however the dependence is much more pronounced in SFC. The mobile phase sojourn time decrease from 65.3 ms to 1.2 ms under low pressure conditions as

the applied flow rate increase, while the stationary phase residence times varies between 804.9 ms and 6.0 ms.

It was found that the stationary phase sojourn times in SFC are about one-half of those in UHPLC, at the optimum mobile phase velocities, while the number of the mass transfer events is in the same range. The mobile phase residence times take similar values at high flow-rates as the mobile phase density and thus the apparent phase ratio of the column becomes more similar in the two chromatographic modes.

The mobile phase sojourn times are less dependent from the mobile phase conditions in case of the SFC measurements, oppositely the sojourn times in the stationary phase depend strongly on the pressure and mobile phase settings.

The number of mass transfers events was found as the most characteristic property in the determination of the efficiency of the measurements. The value of the events was found to be in the range of  $n = 15\,000\text{--}20\,000$  at high flow-rates in SFC and also in HPLC.

By and large, at high linear velocities the mass-transfer properties of SFC and HPLC are rather similar; both the number of mass transfers and the sojourn times are in the same range.

## 5 Thesis statements

1. I have identified the different sources of sample band spreading occurring at the separation of small molecules in ultra high performance liquid chromatography columns, and used that information for the characterization of the effect of frictional heating on efficiency. I have demonstrated that the emerging temperature heterogeneities in the mobile phase provide band spreading comparable to the sum of the external mass-transfer and axial dispersion contributions.
2. I have tested the kinetic performance of a series of  $2.1 \times 50$  mm monolithic and packed columns with different type of particles, emphasizing the sample band broadening in the vicinity of the column ends using the column reversal method. According to this, I have concluded that the local efficiency at the two respective column ends differ from each other in case of the columns packed with slurry packing procedure.  
  
I found that the monolithic MonoTower column provides outstanding performance in case of early eluting compounds, which can be attributed to the moderate mobile phase dispersion caused by the lack of frits in the simple column hardware.
3. I have made the comparison of the intraparticle mass-transfer in superficially porous and fully porous columns with the subtraction of the band broadening contributions of the mobile phase dispersion and the external mass-transfer resistance from experimentally recorded peaks of insulin. I have identified intraparticle diffusion as the additional effect of the pore and surface diffusions, and have demonstrated that surface diffusion is the dominant in the overall intraparticle diffusion.
4. I have studied the chromatographic behaviour of small molecules in supercritical fluid chromatography (SFC) and in reversed phase liquid chromatography (RPLC) using the stochastic model of chromatography. I have observed similar mass-transfer properties at high linear velocities regarding the number of mass transfer events and sojourn times in both cases. I have demonstrated that the change of the mobile phase density with the applied flow rate causes broader variation in the mass-transfer coefficients, especially when the conditions are set close to the supercritical point of the carbon-dioxide mobile phase.

## 6 Publications related to the thesis

Nándor Lambert, Miyazaki Shota, Ohira Masayoshi, Tanaka Nobuo, Attila Felinger  
Comparison of the kinetic performance of different columns for fast liquid chromatography, emphasizing the contributions of column end structure  
Journal of Chromatography A 1473: pp. 99-108. (2016) IF=3.981

Nándor Lambert, Attila Felinger  
Performance of the same column in supercritical fluid chromatography and in liquid chromatography  
Journal of Chromatography A 1409: pp. 234-240. (2015) IF=3.926

Nándor Lambert, Ibolya Kiss, Attila Felinger  
Mass-transfer properties of insulin on coreshell and fullyporous stationary phases  
Journal of Chromatography A 1366: pp. 84-91. (2014) IF=4.169

### 6.1 Related conference presentations

#### Poster presentations

HPLC 2011

36th International Symposium on High Performance Liquid Phase Separations and Related Techniques, Budapest, Hungary, June 19-23, 2011

Nándor Lambert, Attila Felinger

Study of Axial Dispersion with Peak Parking in Different Columns

ISSSB 2011

11th International Symposium and Summer School on Bioanalysis, Austria, Graz, September 18-28, 2011

Nándor Lambert, Attila Felinger

Study of axial dispersion with peak parking

ISSSB 2012

12th International Symposium and Summer School on Bioanalysis, Cluj-Napoca July 4-14, 2012

Nándor Lambert, Attila Felinger

Mass-transfer kinetics of biomolecules in chromatographic columns with porous or coreshell packing materials

MSB 2012

27th International Symposium on MicroScale Bioseparations and Analyses, Geneva, Switzerland, February 12–15, 2012

Nándor Lambert, Attila Felinger

Study of the effective diffusion in coreshell packed columns under stagnant conditions

HPLC 2013

39th International Symposium on High-Performance-Liquid-Phase Separations and Related Techniques, Amsterdam, The Netherlands, June 16-20, 2013

Nándor Lambert, Attila Felinger

Stochastic analysis of mass-transfer properties in Supercritical Fluid Chromatography and in Liquid Chromatography

MSB 2014

30th International Symposium on MicroScale Bioseparations and Analyses, Pécs, Hungary, April 27 - May 1, 2014

Nándor Lambert, Attila Felinger

Evaluation of the mass-transfer properties in chromatographic columns packed with sub-2- $\mu\text{m}$  particles

ISC 2014

30th International Symposium on Chromatography, Salzburg, Austria, September 14-18, 2014,

Nándor Lambert, Attila Felinger

The effect of the frictional heat in chromatographic columns packed with sub-2- $\mu\text{m}$  particles

BS 2015

11th Balaton Symposium on High-Performance Separation Methods, Siófok, Hungary, September 2-4, 2015,

Nándor Lambert, Attila Felinger, Shota Miyazaki, Masayoshi Ohira, Nobuo Tanaka

Comparison of the kinetic performance of different packing materials for fast liquid chromatography

HPLC 2017

45th International Symposium on High Performance Liquid Phase Separations and Related Techniques, Prague, Czech Republic June 18-22, 2017

Nándor Lambert, Attila Felinger.

Analysis of the mass-transfer properties in chromatographic columns using total pore blocking method

## **Oral presentations**

### **CECE 2013**

10th International Interdisciplinary Meeting on Bioanalysis, Pécs, Hungary, April 25-27, 2013

Nándor Lambert, Attila Felinger

Comparison of overall mass-transfer coefficients of Supercritical Fluid Chromatography and Liquid Chromatography

### **IDK 2013**

9th János Szentágothai Interdisciplinary Conference 2013, Pécs Hungary, May 3-4, 2013

Nándor Lambert, Attila Felinger

Determination of overall mass-transfer coefficients in Supercritical Fluid Chromatography and in Liquid Chromatography

### **IDC 2014**

Interdisciplinary Doctoral Conference 2014, Pécs, Hungary, April 15-17, 2014

Nándor Lambert, Attila Felinger

Evaluation of the mass-transfer properties in liquid chromatographic columns

### **BS 2017**

12th Balaton Symposium on High-Performance Separation Methods, Siófok, Hungary, September 6-8 , 2017 Nándor Lambert , Dóra Zelenyánszki, Attila Felinger

Characterization of Stationary Phases for Fast Liquid Chromatography



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